

HYDROLOGICAL PROCESSES

Hydrol. Process. **18**, 1927–1939 (2004)

Published online 12 May 2004 in Wiley InterScience (www.interscience.wiley.com). DOI: 10.1002/hyp.1458

Estimating river discharge from very high-resolution satellite data: a case study in the Yangtze River, China

Kaiqin Xu,¹ Jiqun Zhang,^{1,2*} Masataka Watanabe¹ and Chunpeng Sun³¹ National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan² State Key Laboratory of Resources and Environmental Information System, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, People's Republic of China³ Hydrology Bureau, Ministry of Water Resources of China, Beijing 100053, People's Republic of China

Abstract:

The measurement of river discharge is necessary for understanding many water-related issues. Traditionally, river discharge is estimated by measuring water stage and converting the measurement to discharge by using a stage–discharge rating curve. Our proposed method for the first time couples the measurement of water-surface width with river width–stage and stage–discharge rating curves by using very high-resolution satellite data. We used it to estimate the discharge in the Yangtze (Changjiang) River as a case study. The discharges estimated at four stations from five QuickBird-2 images matched the ground observation data very well, demonstrating that the proposed approach can be regarded as ancillary to traditional field measurement methods or other remote methods to estimate river discharge. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS Yangtze (Changjiang) River; river discharge; water stage; very high-resolution satellite data

INTRODUCTION

Many applications of both water resource management and agricultural management require knowledge of river discharge. Currently, river discharge is estimated by directly measuring flow in the field, and is derived from stage data through the use of a stage–discharge rating curve. Despite the importance of river discharge information, any comprehensive monitoring network faces numerous technological, economic, and institutional obstacles (Vorosmarty *et al.*, 1999). For many rivers, discharge measurements are either nonexistent or not available quickly. This is especially true in underdeveloped countries, for whom the cost of establishing and maintaining a dense network of stream gauges is prohibitive. During flood season, it is usually impossible or impractical to measure peak discharges, even though peak information is very important. For example, road closures might make it impossible to reach a site, or torrential floods may make it unsafe to use conventional methods. Consequently, many peak discharges must be determined by indirect methods after the flood has passed. Thus, a method that uses remotely sensed data to estimate discharge would be beneficial from an economic or safety perspective and will enhance discharge monitoring methods.

Satellite data could provide unprecedented global coverage of critical hydrologic data that are logistically and economically impossible to obtain through ground-based observation networks. The potential of remote sensing to provide information to hydrologists and water resource practitioners has long been recognized (Usachev, 1983; Liu *et al.*, 1983; Koblinsky *et al.*, 1993). The increasing number of satellites and airborne platforms, along with advances in computer hardware and software technology, make it possible to measure and evaluate large numbers of watershed physical characteristics and state variables (Brakenridge *et al.*,

* Correspondence to: Jiqun Zhang, Watershed Management Research Team, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Japan. E-mail: zhang.jiqun@nies.go.jp

Received 18 February 2003

Accepted 9 June 2003

1994; Birkett, 1995, 1998; Al-Khudhairy *et al.*, 2001). The ability to monitor rivers by satellite will become increasingly valuable and important to scientists attempting to understand rivers and the hydrologic cycle.

Up to now, only a few studies have used satellite data to estimate river discharge. Smith *et al.* (1995, 1996; Smith, 1997) suggested that European remote sensing (ERS) synthetic aperture radar (SAR) data are suitable for estimating instantaneous discharge over several channels of a braided river. However, it is probably not possible to use this technique successfully for braided rivers smaller than the one Smith and coworkers studied, owing to the 25 m nominal spatial resolution of ERS SAR data. Costa *et al.* (2000) described an experiment to take non-contact, open-channel discharge measurements. They used ground-penetrating radar and pulsed Doppler radar, to measure channel cross-sectional area and surface velocity respectively. However, this local approach lacks the broad-scale view necessary for defining discharge in complex lowland terrain with water bodies and wetlands (Alsdorf *et al.*, 2001b). Centimetre-scale water-level changes have been measured by using satellite radar altimeter data (Birkett, 1998) and interferometric processing of SAR data (Alsdorf *et al.*, 2000, 2001a). As altimetry is a profiling and not an imaging technique, it is applicable only to water bodies greater than about 1 km in width. Interferometric radar measurements of water-level changes require the acquisition of two SAR images from identical (or nearly identical) viewing geometries, and the two images are coregistered to sub-pixel accuracy for subtraction of the complex phase and amplitude values of each pixel.

On the basis of these studies, two possible approaches to estimating river discharge by using satellite-based data can be summarized as follows:

1. Measure the water surface level by using radar altimeter data or interferometric radar techniques; then convert the data to river discharge via a stage–discharge rating curve.
2. Correlate satellite-derived water surface areas with ground measurements of discharge.

The first approach is restricted to large rivers, and its complicated process usually makes it difficult to use. One major obstacle of the second approach is that a large number of satellite images are required in order to construct an empirical rating curve between satellite-derived water information and river discharge.

Since the launch of the IKONOS satellite in 1999 and the QuickBird-2 satellite in 2001, images with very high ground resolution (1 m scale) have been commercially available. These images make detailed Earth observations feasible in a way not provided by other medium- to small-scale images, such as those from Landsat and SPOT. It is now possible for hydrologists to tackle previously unsolved questions; for example, hydrographic information obtained from satellite data can be used for estimating river discharge. As an adjunct to traditional methods or other remote methods, we have developed an efficient method that focuses on the measurement of water-surface width coupled with river width–stage and the stage–discharge relationship, and have validated it in the Yangtze River.

ESTIMATING RIVER DISCHARGE FROM VERY HIGH-RESOLUTION SATELLITE DATA

Fundamentals of river discharge estimation

The discharge Q at a river cross-section is the volumetric flow rate through that cross-section, and can be given by

$$Q = \int_A V dA \quad (1)$$

$$A = WY \quad (2)$$

where V is the average velocity, W is the water-surface width, Y is the average depth, and A is the cross-sectional area perpendicular to the flow direction. Discharge estimation requires the determination or estimation

of the channel cross-sectional area, including average depth, width, and average stream flow velocity. Remote data collection by aerial photography and satellite imagery is restricted to surface features, such as channel width and water-surface width, but not Y or V (Costa *et al.*, 2000). Famous hydraulic relations, such as the Manning equation, have been used to estimate velocity from the channel geometry (Chow, 1959). Use of this equation requires knowledge of the channel resistance, which is typically understood to be a function largely of the sediment conditions within the channel. Since information on the specific sediment conditions within a channel reach cannot be obtained directly from satellite or aerial imagery, the Manning equation cannot be used directly to estimate discharge. Some researchers (Williams, 1978; Dingman and Palaia, 1999) have noted the strong relationship between river discharge and water-surface width (channel forming). This kind of relationship is the starting point for determining discharge from satellite-derived information if enough satellite imagery can be collected to determine the relationship between satellite-derived water width and discharge measured *in situ*. For almost all medium to large rivers, stage–discharge rating curves have been constructed for control sections along the rivers, and the corresponding river channel geometry has been measured and updated every year. This information forms the foundation for estimating discharge from satellite data. Through the use of the stage–discharge rating curve and channel geometry, satellite-derived water-surface width can be converted to river discharge. The critical problem is how to measure water-surface width with satisfactory accuracy.

The QuickBird-2 satellite, which was launched on 18 October 2001, is currently the only spacecraft able to offer sub-metre resolution imagery. Table I gives some specifications of this satellite. A remarkable characteristic of QuickBird-2 imagery is that its spatial resolution has reached 0.61 m (nadir). This means it can be used to determine water-surface width with satisfactory accuracy.

Estimating river discharge

Once the relationships between river discharge and river stage and between river stage and water-surface width have been established, they can be used to estimate river discharge from satellite data alone. Our method (Figure 1) can be summarized as follows:

1. Construct stage–discharge rating curve according to hydrologic data from the study site.
2. Field-survey the channel geometry or construct the relationship between water-surface width and water stage according to hydrologic data from the control cross-section.
3. Identify and measure water-surface width in the control cross-section from QuickBird-2 imagery.
4. Convert satellite-derived water-surface width to water stage on the basis of information collected in step 2.
5. Convert water stage to river discharge from curve constructed in step 1.

The crucial step in this method is determining the water-surface width precisely enough. This method has limited utility without very high-resolution satellite data. The expected accuracy of this method is subject to

Table I. General specifications of QuickBird-2 satellite

Item	Features	Item	Features
Orbit altitude	450 km	Panchromatic pixel size	0.61 m (Nadir)
Average revisit time	1–3.5 days	Panchromatic spectral range	450–900 nm
Field of regard	$\pm 30^\circ$	Multispectral pixel size	2.44 m (nadir)
Scene size	Snapshot: $16.5 \times 16.5 \text{ km}^2$ Area: $32 \times 32 \text{ km}^2$ Strip: $16.5 \times 165 \text{ km}^2$	Multispectral spectral range	Blue 450–520 nm Green 520–600 nm Red 630–690 nm NIR 760–900 nm

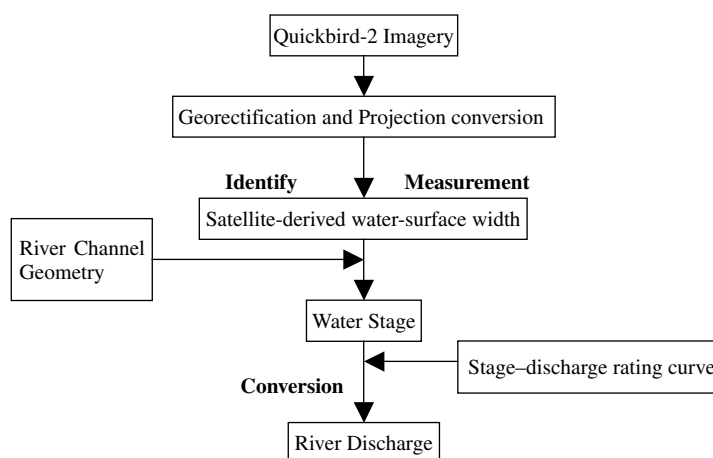


Figure 1. Flowchart of the proposed method for estimating river discharge

statistical variance in the natural hydrologic systems used to calibrate the method, and in the resolution of the remote imagery.

CASE STUDY IN YANGTZE RIVER

Study area

The Yangtze (Changjiang) River, the largest river in China and third largest in the world, originates in the Qinghai Tibet Plateau and flows about 6300 km eastwards to the East China Sea. We selected four sites in the Yangtze River (Figure 2) to validate the proposed method.

Datong (117.62°E, 30.76°N), located in the lower reach of the Yangtze River, about 624 km from the Yangtze Estuary, is the last hydrological gauging station located in the main stem of the Yangtze River before the river water flows into the East China Sea. The drainage area above Datong hydrological gauging station is about $1.705 \times 10^6 \text{ km}^2$.

Luoshan (113.32°E, 29.65°N) is located in the middle reach of the Yangtze River, about 1345 km from the Yangtze Estuary. Almost every year, the area is visited by floodwaters. The drainage area is about $1.296 \times 10^6 \text{ km}^2$. According to historical data, in an ordinary year the discharge range is approximately $(0.45\text{--}6) \times 10^4 \text{ m}^3 \text{ s}^{-1}$.

Yichang (111.28°E, 30.70°N), a communication hub for Sichuan and Hubei Provinces, is located in western Hubei, in the upper-middle reach of the Yangtze River, about 1837 km from the Yangtze Estuary. Yichang is known as the 'Gateway to the Three Gorges'. The GeZhouba Dam, completed at the end of the 1980s, is located here, and the famous Three Gorges Dam is only about 40 km to the north. The drainage area above Yichang hydrological gauging station is about $1.003 \times 10^6 \text{ km}^2$. According to historical data, in an ordinary year the discharge range is approximately $(2.0\text{--}4.0) \times 10^4 \text{ m}^3 \text{ s}^{-1}$ during the flood season to only about $0.4 \times 10^4 \text{ m}^3 \text{ s}^{-1}$ during the dry season.

Cuntan (106.63°E, 29.64°N) is located in the upper reach of the Yangtze River, about 2506 km from the Yangtze Estuary. It is one of the most important hydrological gauging stations located in the main stem of the Yangtze River and the drainage area is about $0.867 \times 10^6 \text{ km}^2$.

Relationship between river stage and discharge

The conversion from river stage to discharge is made with a stage-discharge rating curve. The curves for the four sections have changed frequently in recent years, because of the huge amount of the discharge and

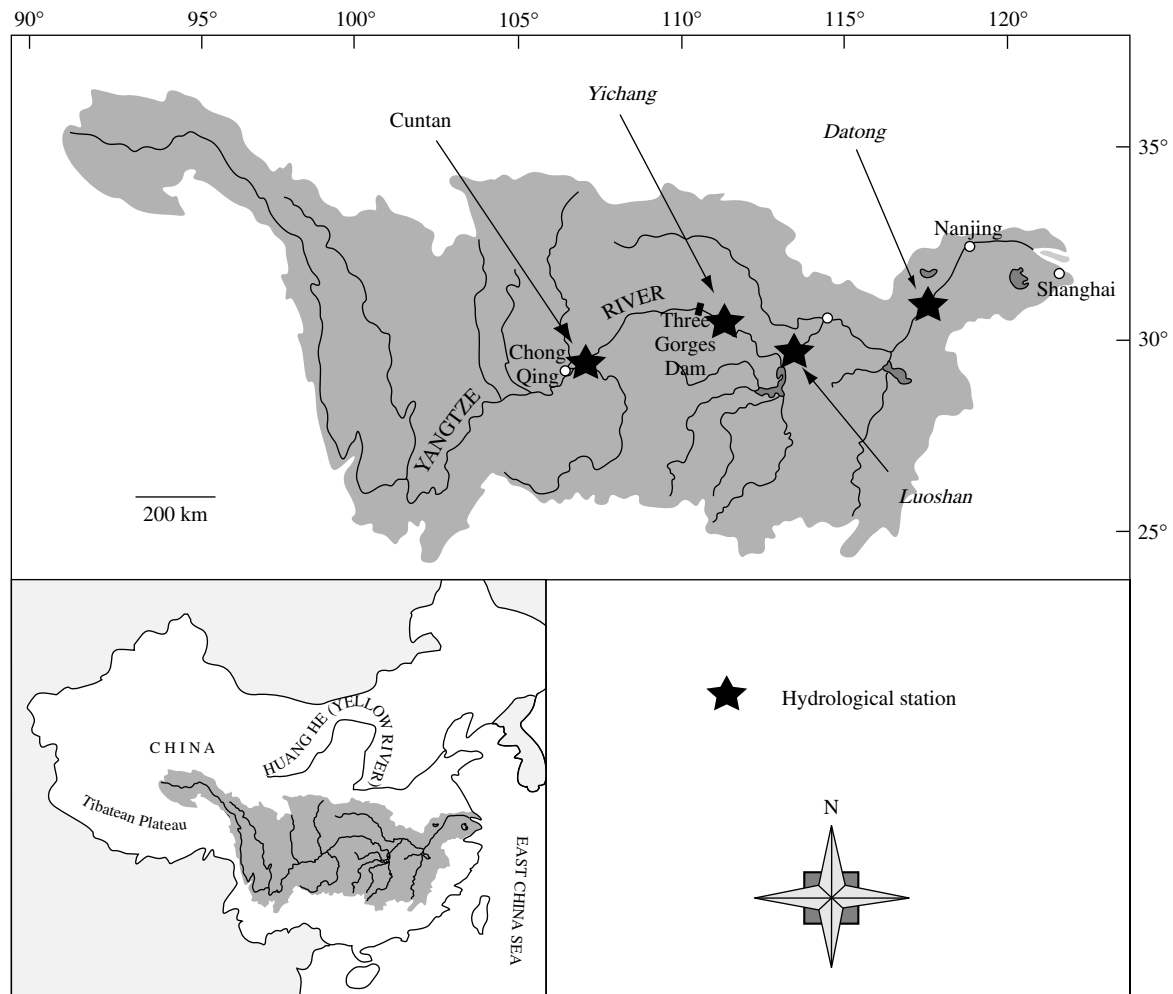


Figure 2. Location of study sites on the Yangtze River

sediment settling and transportation in the river. To reflect the real discharge of the corresponding data of the hydrological stations more exactly, it is necessary to use updated water stage and discharge data rather than historical data. Therefore, four recent years (1998–2001) of water stage and discharge data were acquired at the local hydrological gauging stations. The correlations between H (water stage) and Q (discharge) are plotted in Figure 3. The best power functions are:

$$Q = 891.66H^{1.586} \quad (R^2 = 0.99, \text{ for Datong}) \quad (3)$$

$$Q = 0.0719H^{3.8813} \quad (R^2 = 0.99, \text{ for Luoshan}) \quad (4)$$

$$Q = 10^{-10}H^{8.5640} \quad (R^2 = 0.99, \text{ for Yichang}) \quad (5)$$

$$Q = -0.9603H^3 + 535.13H^2 - 96369H + 5.657 \times 10^6 \quad (R^2 = 0.99, \text{ for Cuntan}) \quad (6)$$

Once a relationship has been established, it can be used to convert river stages to river discharges.

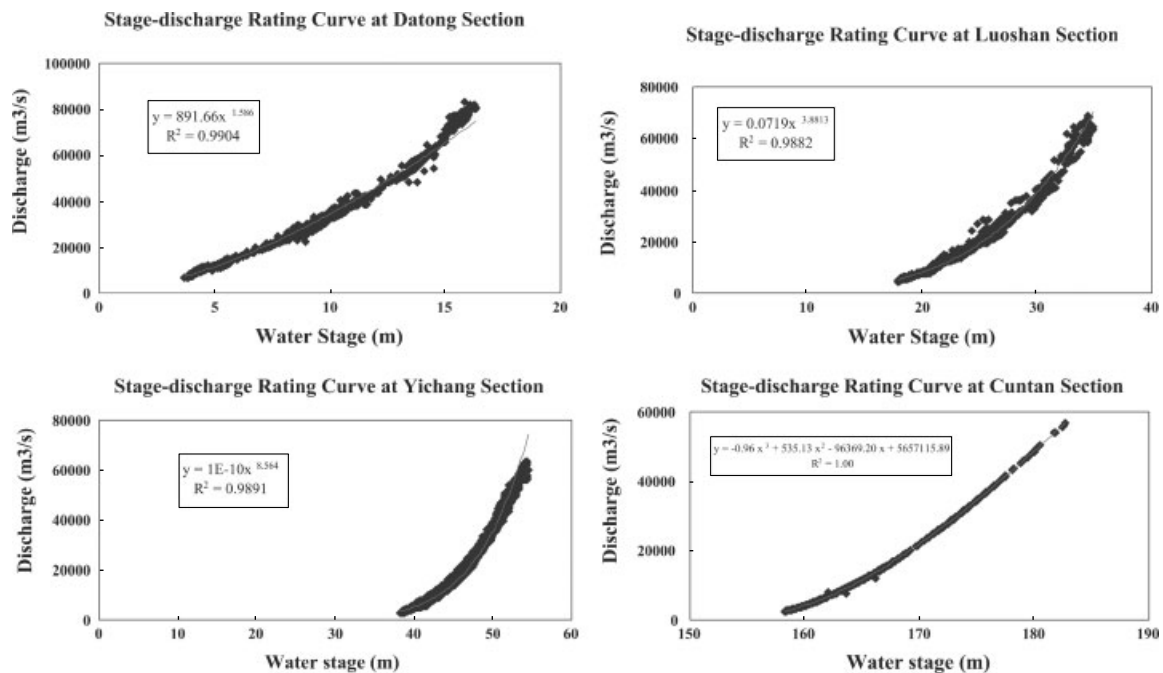


Figure 3. Stage–discharge rating curve for the Yangtze River

River channel geometry in the control cross-section

To convert satellite measurement data to discharge data, it is essential first to measure the geometry of the river channel or to determine the relationship between water-surface width and water stage. Figure 4 shows the river channel geometry at each study site. Obviously, the river channels at those sites are trapezoidal, where small changes in depth produce corresponding changes in water-surface width, making it possible to derive water stage from water-surface width. In order to convert water-surface width to water stage, a look-up table should be built based on the river channel geometry. In a normal year, the water stage in Yichang section ranges from 38 to 55 m. Table III gives the look-up table of water stage and water-surface width in the Yichang section. Similar procedures were applied to other sections.

Field survey of ground control points

Highly accurate ground control points (GCPs) are necessary in order to rectify QuickBird-2 satellite imagery. A field survey was carried out in February 2002 to select and measure GCPs accurately. Three dual-frequency global positioning system receivers were used in the survey (Trimble 4000SSE and 4000SSI). For each study site, more than 20 GCPs (including two at the cross-section) were surveyed. The computation was carried out

Table II. Specifications of the QuickBird-2 images used to estimate discharge

Acquired date	Cover area	Centre location	Resolution (m)
29 Mar 2002 03:23:27GMT	Yichang	111°28'08"E, 30°6'864"N	0.64
04 Jun 2002 03:18:01GMT	Yichang	111°27'92"E, 30°7'152"N	0.64
03 Nov 2002 03:08:13GMT	Luoshan	113°32'37"E, 29°6'547"N	0.61
12 Jan 2003 02:46:37GMT	Datong	117°6'193"E, 30°7'641"N	0.63
03 Dec 2002 03:39:35GMT	Cuntan	106°6'325"E, 29°6'408"N	0.64

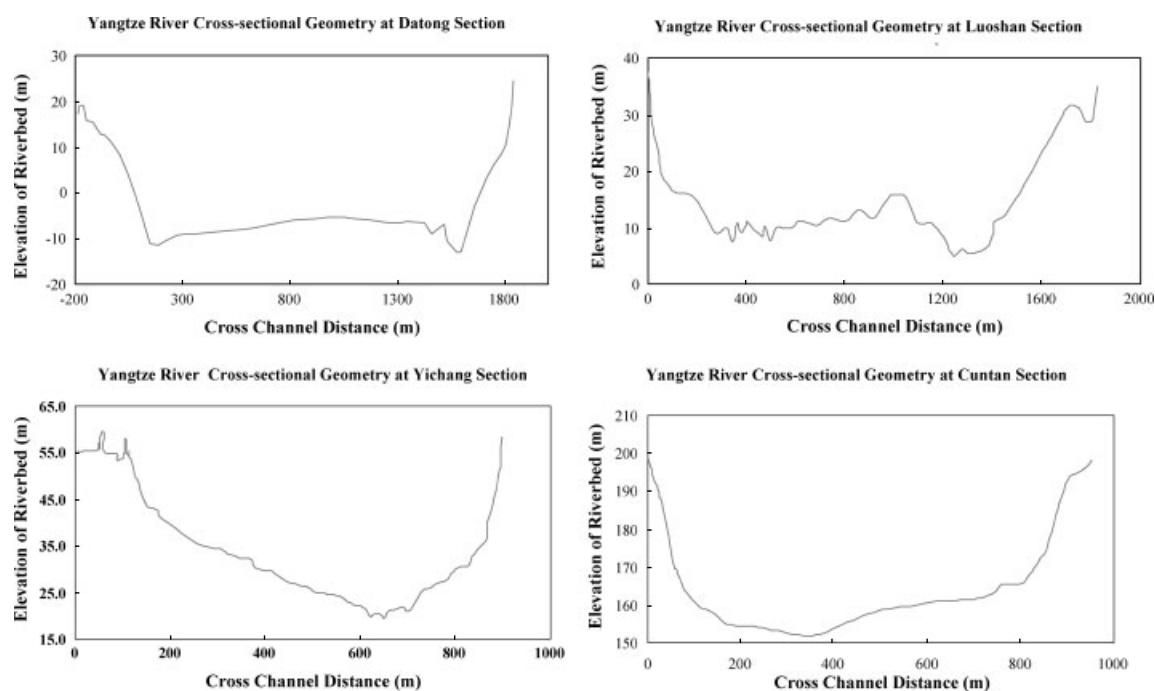


Figure 4. Cross-sectional geometry in the Yangtze River

with the GAMIT program from the Massachusetts Institute of Technology. Finally, geographic coordinates in the WGS-84 datum and three-dimensional coordinates in the UTM system were obtained. The horizontal standard errors of these control points were better than 0.05 m.

Identification and measurement of water-surface width from satellite imagery

Three QuickBird-2 images from four study sites have been acquired. The specifications of these images are listed in Table II. Figure 5 is a QuickBird-2 image of the Yichang section acquired on 29 March 2002. Extracting quantitative water information from imagery is a critical step in estimating discharge. Before trying to determine the water width information from satellite imagery, we must rectify the imagery to a suitable projection.

As the study sites in which we are interested belong to small and flat-water surfaces, we rectify the satellite imagery by applying polynomial modelling instead of orthorectification. Figure 6 is a GCP distribution map of the Yichang section, which was plotted by a surveyor. About 10 GCPs were selected to rectify the imagery to an azimuthal equidistant map projection. The processing described here was done with the image-processing software ERDAS Imagine 8.4. Two GCPs at the control cross-section were selected and measured (Figure 6). Two points, where the cross-section line intersects the river's edges, were identified from the QuickBird-2 images (Figure 7). The distance between those two points is the water-surface width B , which was measured with measurement tools in ERDAS Imagine. Figure 8 shows a flowchart of the proposed procedure for calculating B . The water-surface width on the image is 668.86 m for the Yichang section acquired on 29 March 2002.

Estimating river discharge and comparing it with ground-measured discharge

Using the width obtained (668.86 m) from the above procedure, the corresponding water stage H was calculated from the corresponding look-up table (Table III) as 39.82 m. From Equation (5), the water stage was converted to a discharge $Q = 5050 \text{ m}^3 \text{ s}^{-1}$ for the Yichang section.

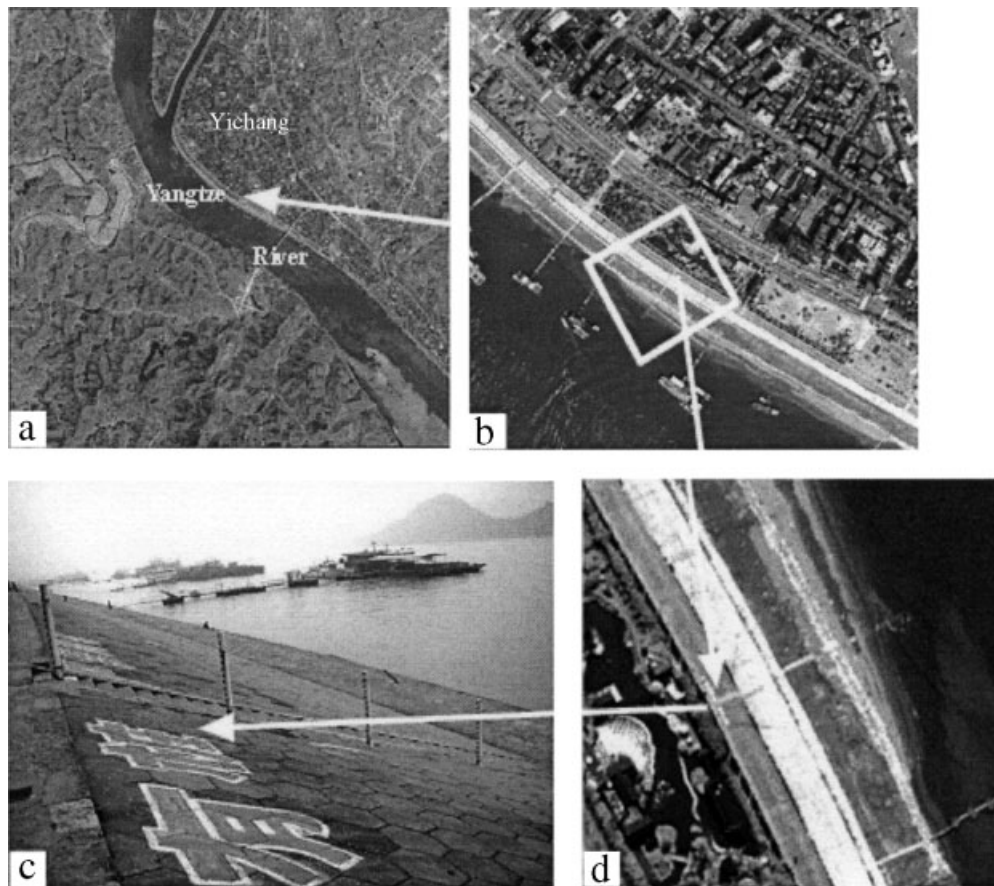


Figure 5. QuickBird-2 satellite image of Yichang section in the Yangtze River (acquired on 29 March 2002): (a) the QuickBird-2 image; (b) control cross-section on the left river bank; (c) the zoom of the left river bank on the control cross bank; (d) photograph of the left riverbank at the Yichang control section

From Table II, we know that the acquisition time (Greenwich mean time, GMT) of this image was 03:23h, 29 March 2002. Yichang is located eight time zones east of GMT, so the acquisition time can be converted to the local time of 11:23h, 29 March 2002. So the satellite-derived discharge in the Yichang section of the Yangtze River at 11:23h on 29 March 2002 was $5050 \text{ m}^3 \text{ s}^{-1}$.

We also collected river discharge data from the Yichang hydrological gauging station. The measured discharge at 08:00h on 29 March 2002 was $5150 \text{ m}^3 \text{ s}^{-1}$. It can be seen that the difference between the estimated and measured discharge at Yichang section is $100 \text{ m}^3 \text{ s}^{-1}$; thus, the accuracy is 97% (Table IV).

By using the same procedures and corresponding equations, we processed other QuickBird-2 imageries acquired in 2002 and 2003. Table IV lists satellite-derived discharge and ground-measured discharge in the main hydrological stations in the Yangtze River. Generally speaking, the calculated results agree well with the ground-measured data, demonstrating that the present method can be used for discharge estimation in rivers.

DISCUSSION

Result analysis and improvement

The spatial resolution of most of the current satellite imagery data is too coarse to be used to determine accurate water edge lines for estimating discharge. However, the QuickBird-2 image, with very high spatial

Table III. Look-up table of water stage and water surface width at the Yichang control cross-section

Water stage	Water surface width (m)
55	781.54
54	778.79
53	775.22
52	771.33
51	766.81
50	762.29
49	755.76
48	751.20
47	746.41
46	741.30
45	736.33
44	715.29
43	710.95
42	697.34
41	689.18
40	672.83
39	651.00
38	643.79

Table IV. Comparison between satellite-derived and ground-measured discharge

Station	Water-surface width (m)	River discharge ($\text{m}^3 \text{s}^{-1}$)				Accuracy (%)
		Satellite-derived	Time	Ground-measured	Time	
Yichang	669	5 050	11:23am	5 150	8:00am	98
	735	14 163	11:18am	14 600	8:00am	97
Luoshan	1 587	18 326	11:08am	19 700	8:00am	93
Datong	1 747	18 333	10:46am	17 700	8:00am	96
Cuntan	471	4 278	11:39am	4 650	8:00am	92

resolution, provides a good basis for identifying and monitoring water-related structural changes. This has made our proposed method reliable and easy to use.

We have identified two sources of error. (1) Systematic error in the water stage–discharge rating curve at the control cross-section. Owing to the complicated hydraulic system in the Yangtze River, error exists when a water stage value is converted to river discharge by using the water stage–discharge rating curve. For example, Figure 3 shows that, at a water stage of $H = 40$ m, the corresponding field-measured discharge Q varies from 3700 to 5660 $\text{m}^3 \text{s}^{-1}$. In this study section, discharge is a function not only of water stage but also of slope. To improve the accuracy of conversion from water stage to discharge, a more complex function should be formulated, one that takes into account water stage, water surface slope, and other factors. (2) Differences in time of acquisition between the satellite and the gauging station. For example, QuickBird-2 took its image of the Yichang section at 11:23h, whereas the measurement at the Yichang hydrological gauging station was taken at 08:00h. Water current changes on time scales shorter than this.

Restriction and potential for application to other rivers or water bodies

The methodology described in this paper allows us to estimate river discharge from very high-resolution satellite data. This result was not possible before this source of data was available for non-military applications.

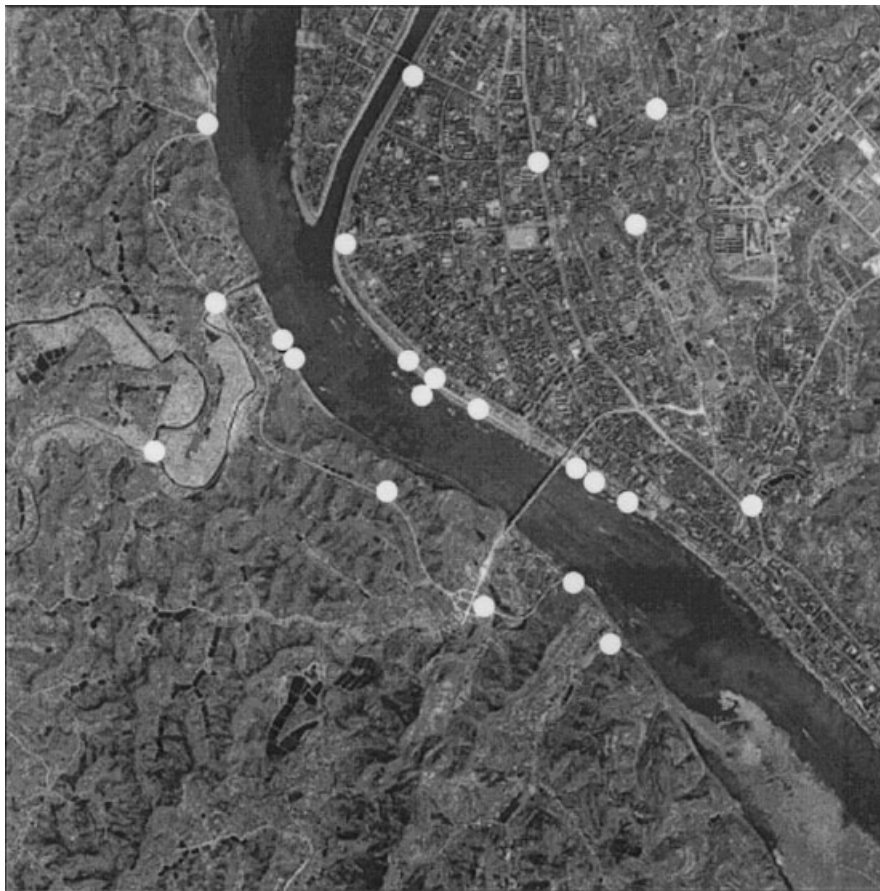


Figure 6. Map of the ground control points (GCPs) in the Yichang study area

However, the cost of images, sampling frequency, and cloud cover restrict its use. Thus, it supplements traditional methods or other remote methods instead of replacing them. Rapid improvements in satellite technology should bring down prices and improve the sampling frequency. Some commercial satellites with 1 m resolution SAR data have or will be launched in the near future (e.g. RADAR1 (2002), SkyMed COSMO (2002), and Terra SAR-X (mid-2005)). Their data will be compatible in resolution with optical systems such as QuickBird-2. Optical sensor data are restricted by cloud conditions, but SAR data can be obtained in any weather conditions. The use of SAR data will make our method more valuable.

This method can be applied to other large, medium-sized, or even small rivers where small changes in depth produce corresponding changes in surface-water width, and stage–discharge curves and river channel geometry can be determined by stream gauging. In the case of small rivers, however, certain influences that could be ignored for large rivers must be taken into account. These include encroachment by vegetation and debris, which can result in a significant reduction in bank-full width. Differences between active and bank-full widths in smaller rivers should be determined before this method is used.

For river sections where neither river channel geometry nor relationship between water stage and water-surface width are available, determination of absolute discharge poses a more difficult problem. However, if a series of satellite imagery covered the same river section from the dry season through to the flood season, and if the instantaneous discharge was measured on the ground, then it would be possible to construct the rating curve between satellite-derived section width (or area) and discharge. Based on this rating curve, it

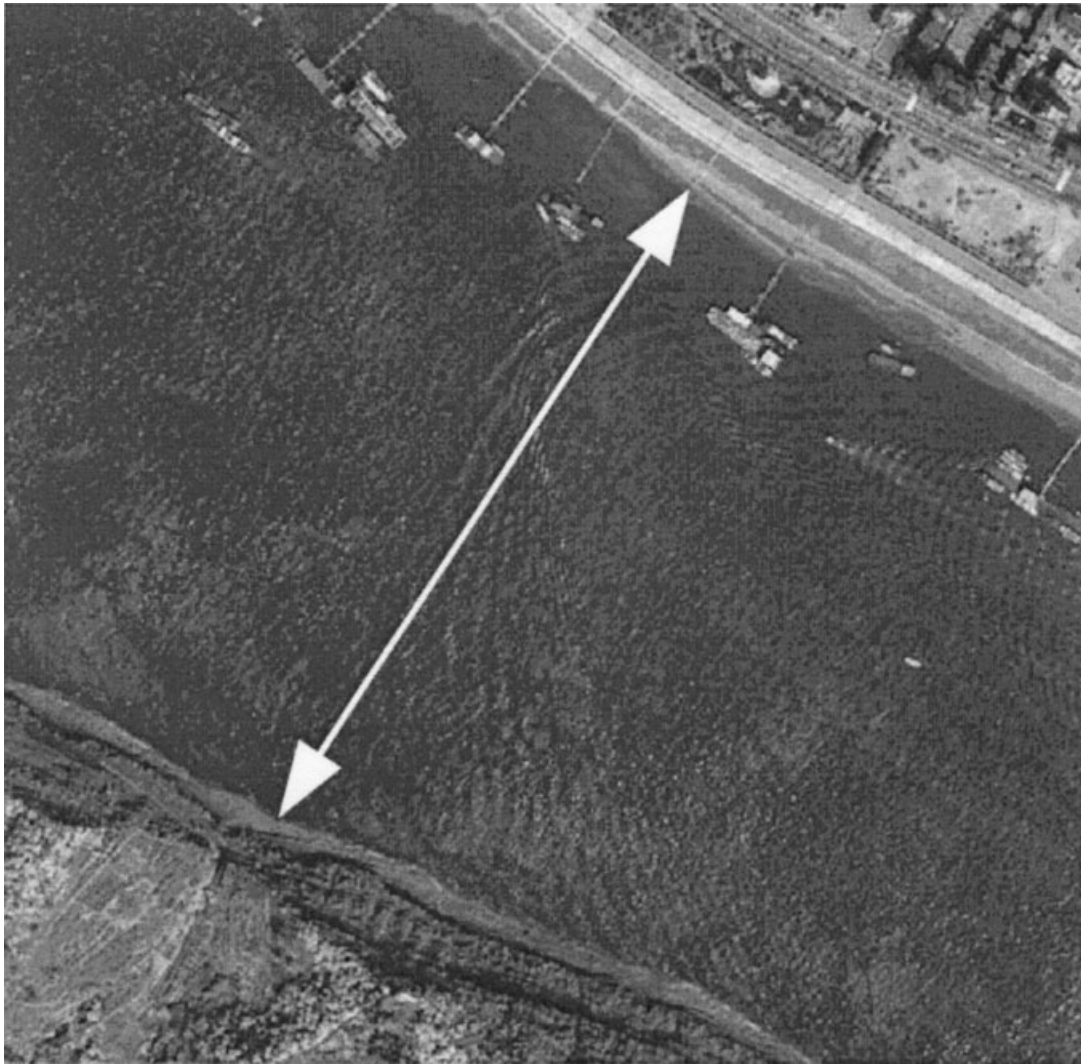


Figure 7. Water-surface width at the Yichang control cross-section

would be possible to estimate discharge from satellite images. The weakness of this method is that a lot of satellite imagery covering the study site must be acquired; this will be time-consuming and costly.

A similar approach can be used in other, related fields. For example, the extent, elevation, and volume of water bodies are important parameters for assessing the state of lakes, reservoirs, or wetlands. Water stage is another important parameter for understanding and managing large storages in lakes and reservoirs. In this case, our method makes it possible to infer water elevations from satellite images. Relations between water depth and other measurable parameters can be used to convert remotely measured areas of lakes or reservoirs into volumes. This is particularly true of cases where small changes in depth produce large changes in perimeter and area.

Prospects

Discharge estimations require determination or estimation of the channel cross-sectional area, including average width and depth, as well as average stream flow velocity. Current satellite imagery and other remote

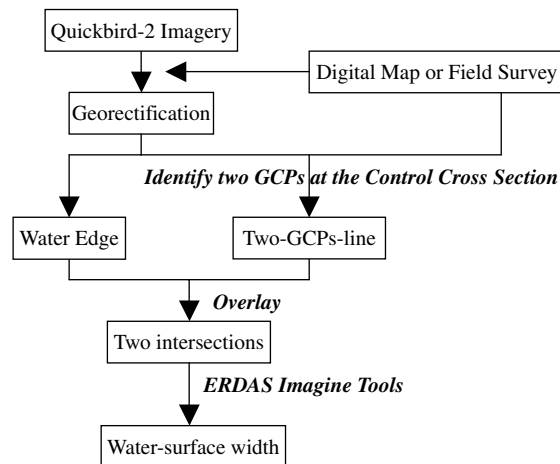


Figure 8. Flowchart of the proposed method for calculating water surface width

data sources are restricted in their ability to determine channel and water-surface width, channel slope, and channel platform shape. Recent advances in satellite-borne lidar and radar sensors allow the potential for direct measurement of surface velocity in rivers at discrete points in a channel section. Depth and average velocity are the two critical hydrographic variables that cannot, at present, be directly assessed from satellite imagery or other remote data sources. Thus, any method of estimating discharge from remote data sources must, at a minimum, be able to estimate the channel depth. Given surface velocity as a measured variable, a method must also be developed that can use point surface velocity to estimate the average velocity in a channel reach. An advantage of using surface velocity as an input variable is that discharge can be measured directly at any given time, provided that appropriate estimations of average velocity and depth are derived. This kind of method has the potential to be useful for remote regions of the globe where *in situ* data are not readily available.

CONCLUSIONS

Traditionally, a river's discharge is monitored by measuring its water stage and then converting it to river discharge by using a stage–discharge rating curve. As an adjunct to the traditional method, the method described in this paper for the first time focuses on the estimation of river discharge from very high-resolution satellite data. The method is based on a series of simple procedures: water-surface width measurements coupled with river width–stage and stage–discharge rating curves derived from field survey. Using QuickBird-2 imagery, we used the method to estimate the discharge in the Yangtze River. The estimated discharges at four stations matched the ground measurements very well, suggesting that this approach may be useful for discharge estimation for other medium and large rivers.

Furthermore, because remotely sensed images can be captured more readily these days at high resolution, efficient methods to convert satellite data to geographic information, like the one proposed here, should be very useful for extracting up-to-date and accurate water-related information.

ACKNOWLEDGEMENTS

We would like to thank Professor Malcolm G. Anderson and the anonymous referees, who kindly reviewed an earlier version of this manuscript and provided many valuable comments and suggestions. This work

was carried out at the National Institute for Environmental Studies, with funding from the Ministry of the Environment, Japan. The QuickBird-2 satellite data were provided by Hitachi GIIS, Japan, and acquired by the DigitalGlobe Company, USA. The Yangtze River Water Resources Commission of China collected ground measurements of river discharge. The GCP data were measured and provided by SuperMap GIS Technologies, Inc., China.

REFERENCES

- Al-Khudhairy DHA, Leemhuis C, Hoffmann V, Calaan R, Shepherd IM, Thompson JR, Gavin H, Gasca-Tucker DL. 2001. Monitoring wetland ditch water levels in the North Kent Marshes, UK, using Landsat TM imagery and ground-based measurements. *Hydrological Sciences Journal—Journal des Sciences Hydrologiques* **46**(4): 585–597.
- Alsdorf DE, Melack JM, Dunne T, Mertes LAK, Hess LL, Smith LC. 2000. Interferometric radar measurements of water level changes on the Amazon flood plain. *Nature* **404**: 174–177.
- Alsdorf DE, Smith LC, Melack JM. 2001a. Amazon floodplain water level changes measured with interferometric SIR-C radar. *IEEE Transactions on Geoscience and Remote Sensing* **39**(2): 423–431.
- Alsdorf DE, Birkett CM, Dunne T, Melack J, Hess L. 2001b. Water level changes in a large Amazon lake measured with spaceborne radar interferometry and altimetry. *Geophysical Research Letters* **28**: 2671–2674.
- Birkett CM. 1995. The contribution of Topex/Poseidon to the global monitoring of climatically sensitive lakes. *Journal of Geophysical Research* **100**: 25 179–25 204.
- Birkett CM. 1998. Contribution of the TOPEX NASA radar altimeter to the global monitoring of large rivers and wetlands. *Water Resources Research* **34**: 1223–1239.
- Brakenridge WG, Knox JC, Paylor ED, Magilligan FJ. 1994. Radar remote sensing aids study of the great flood of 1993. *Eos Transactions AGU* **75**(45): 521–527.
- Chow VT. 1959. *Open Channel Hydraulics*. McGraw-Hill: New York.
- Costa JE, Spicer KR, Cheng RT, Haeni PF, Melcher NB, Thurman EM, Plant WJ, Keller WC. 2000. Measuring stream discharge by non-contact methods: a proof-of-concept experiment. *Geophysical Research Letters* **27**: 553–556.
- Dingman SL, Palaia KJ. 1999. Comparison of models for estimating flood quantiles in New Hampshire and Vermont. *Journal of the American Water Resources Association* **35**: 1233–1243.
- Koblinsky CJ, Clarke RT, Brenner AC, Frey H. 1993. Measurement of river stage variations with satellite altimetry. *Water Resources Research* **29**(6): 1839–1848.
- Liu X, Zhang S, Li X. 1983. The application of Landsat image in the surveying of water resources of Dongting Lake. In *Proceedings of the 3rd Asian Conference on Remote Sensing*, Dacca, Bangladesh, 4–7 December 1982. University of Tokyo: Tokyo; D-3-1–D-3-10.
- Smith LC. 1997. Satellite remote sensing of river inundation area, stage, and discharge: a review. *Hydrological Processes* **11**: 1427–1439.
- Smith LC, Isacks BL, Forster RR, Bloom AL, Preuss I. 1995. Estimation of discharge from braided glacial rivers using ERS-1 SAR: first result. *Water Resources Research* **31**: 1325–1329.
- Smith LC, Isacks BL, Bloom AL, Murray AB. 1996. Estimation of discharge from three braided rivers using synthetic aperture radar (SAR) satellite imagery: potential for application to ungauged basins. *Water Resources Research* **32**(7): 2021–2034.
- Usachev VF. 1983. Evaluation of flood plain inundations by remote sensing methods. *Hydrological Applications of Remote Sensing and Remote Data Transmission*, Goodison BE (ed.). IAHS Publication no. 145. IAHS Press: Wallingford; 475–482.
- Vorosmarty C, Birkett C, Dingman L, Lettenmaier DP, Kim Y, Rodrigues E, Emmitt GD. 1999. *NASA Post 2002 Land Surface Hydrology Mission Component for surface water monitoring: HRDRA-SAT, a report from the NASA Post 2002 LSHP Planning Workshop* Irvine, CA, USA, 12–14 April. <http://lshp.gsfc.nasa.gov/missdrft.html>.
- Williams GP. 1978. Bankfull discharge in rivers. *Water Resources Research* **14**: 1141–1154.